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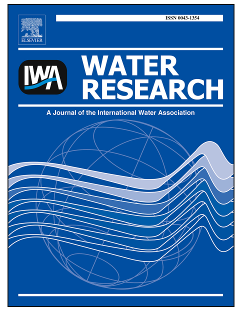

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Definitions of event magnitudes, spatial scales, and goals for climate change adaptation and their importance for innovation and implementation

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Abstract

We examine how core professional and institutional actors in the innovation system conceptualize climate change adaptation in regards to pluvial flooding—and how this influences innovation. We do this through a qualitative case study in Copenhagen with interconnected research rounds, including 32 semi-structured interviews, to strengthen the interpretation and analysis of qualitative data. We find that the term "climate change adaptation" currently has no clearly agreed definition in Copenhagen; instead, different actors use different conceptualizations of climate change adaptation according to the characteristics of their specific innovation and implementation projects. However, there is convergence among actors towards a new cognitive paradigm, whereby economic goals and multifunctionality are linked with cost-benefit analyses for adapting to extreme rain events on a surface water catchment scale. Differences in definitions can lead to both successful innovation and to conflict, and thus they affect the city's capacity for change. Our empirical work suggests that climate change adaptation can be characterized according to three attributes: event magnitudes (everyday, design, and extreme), spatial scales (small/local, medium/urban, and large/national-international), and (a wide range of) goals, thereby resulting in different technology choices.

Key words: City, Climate Change Adaptation, Discourse, Innovation, Stormwater

1. Introduction

It is increasingly recognized that living conditions change and that cities have to adapt to a shifting but uncertain future climate. This process includes a series of transformations to our built environment as well as socio-technical systems and institutions. A central tenet in the adaptation process is the urban water system (IPCC, 2014), in which water supply and stormwater and wastewater management are all highly strained (Pahl-Wostl, 2007). However, exactly what constitutes climate change adaptation is unclear, thereby leading to misunderstandings and conflict among actors.

In Denmark, the urban landscape has started to change over the past 10 years as the country adapts to climate change. This is generally linked to flooding, as several pluvial and costal floods have hit the country; for example, Aarhus experienced a large cloudburst in 2012, Roskilde Fjord experienced major storm surges in 2013 and 2017, and several smaller cities south of Copenhagen in Køge Bay were hit by a major storm surge in 2017. These extreme events should be considered in the context of expected gradual increases in sea levels and rain volumes (IPCC, 2014). Copenhagen has experienced significant damages due to pluvial flooding (Arnbjerg-Nielsen et al., 2015) following extreme rainfall events that hit the city in 2007, 2010, 2011, and 2014. The response from the affected municipalities has been the development of extensive climate change adaptation plans, the most well-known of which are the City of Copenhagen's adaptation plan (Københavns Kommune, 2011) and its Cloudburst Management Plan (Københavns Kommune, 2012). Copenhagen participates with other cities in several international knowledge-sharing activities for climate change adaptation, including international collaboration with New York and Beijing, and participation in the C40 international city network addressing the issue. In these settings, cities are inspired and learn from each other across different contexts, with Copenhagen's planning methodology especially attracting national and international attention (State of Green, 2015).

Policymakers' conceptual understanding of climate change adaptation has been studied previously, primarily in political science literature reviews, focusing on both international publications and planned adaptation projects, e.g. Biagini et al. (2014), and the academic climate change literature, e.g. Smit et al. (2000), who concluded that adaptation can be characterized according to three questions: (i) "Adaptation to what?," (ii) "Who or what adapts?," and (iii) "How does the adaptation occur?" To answer question (i), climate change adaptation should be considered in the context of relevant system characteristics, for example precipitation frequency and/or magnitude. Furthermore, it should be specified whether the adaptation measures are part of a response to a gradual change in climatic conditions or to an increased frequency in extreme events. To answer question (ii), the system definition is also critical, and this includes the spatial scales of the corresponding natural, technical, and social systems. To answer question (iii), adaptation should be considered in the context of the dynamics of overall system change, which Smit et al. (2000) classified as either planned or spontaneous. Biagini et al. (2014) defined ten climate change adaptation categories, namely capacity building, management and planning, practice or behavior, policy, information, physical infrastructure, warning or observing systems, green infrastructure, financing, and technology, emphasizing that many adaptation measures can be placed in several categories. Categories like "practice or behavior," "policy," and "information" show that climate change adaptation may have a multitude of goals, in that it embraces not only the technical urban water system, but also surrounding actors and institutions and as such the entire socio-technical system, which is commonly the case for infrastructural systems (Markard et al., 2012).

The drivers of and barriers to the practical implementation of climate change adaptation is well studied across different cities and climates (Adger et al., 2009; Biesbroek et al., 2011; Ferguson et al., 2013; Hrelja et al., 2015; Kabisch et al., 2016); however, no previous studies on how the definition of climate change adaptation is applied in practice can be found in the academic literature. For stormwater management, which is an aspect of climate change adaptation especially relevant to pluvial flood mitigation, one study of the effect of the cultural context on definitions has been undertaken by Fletcher et al. (2015), who reviewed the terminology involved in urban stormwater management and concluded that local differences can lead to confusion. In Denmark, the term *lokal afledning af regnvand* (LAR; local diversion of stormwater) is applied and encompasses elements of detention, infiltration or harvesting, evapotranspiration, transport, and treatment, which, when combined, become an LAR system (Madsen et al., 2017). Fletcher et al. (2015) stressed the importance of actors being explicit about their definitions and suggested ‘stormwater control measures’ (SCMs) as an all-encompassing term for green infrastructure (GI), low impact development (LID), sustainable urban drainage systems (SUDSs), and water-sensitive urban design (WSUD). Fletcher et al. also stressed the need for explaining “what the measure attempts to control and for what purpose.” Climate change adaptation similarly has cognitive framing difficulties, with multiple and culturally dependent definitions used in both practice and research. One way of defining stormwater management is the three-point approach (3PA), which defines three domains in which important decisions take place: The everyday domain, involving everyday values and rainwater resource utilization; the design domain, encompassing the design and technical optimization of the stormwater system; and the extreme domain, looking at extremes, pluvial flood mitigation, and urban resilience. One should consider all three domains in order to create a resilient stormwater system; however, different types of professionals tend to work in different domains (Fratini et al., 2012). The term ‘climate change adaptation’ is in the 3PA though merely used as a synonym for urban flood risk management and stormwater management, without comprehensively describing what attributes the term entails and what types of measures are included.

No study has previously investigated the relationships between the definition of climate change adaptation applied by practitioners and the change process. This paper therefore investigates how the conceptual understanding of climate change adaptation currently varies across core actors in Copenhagen’s innovation system and how this influences innovation and implementation. This is done in order to explain how climate change adaptation is defined in practice, and to demonstrate the importance of defining event magnitudes, spatial scales, and goals for the ongoing change process.

2. Theory

Our study takes a theoretical system change perspective based on innovation system (IS) theory, which is a field of study evolving from economic studies to incorporate technical and institutional change (Freeman, 1988a). It was first described in full as national systems of innovation (Nelson, 1988), but earlier thoughts are found in technological regimes theory (Nelson and Winter, 1977) and path dependence theory (Dosi, 1982). Innovation is defined here as "the something beyond the invention," but it also includes the process of entering the market, known as "diffusion" (Dosi and Orsenigo, 1988; Lundvall, 2007). The innovation concept distinguishes between product innovation (material goods and services) and (technical or organizational) process innovation (Edquist, 2004; Lundvall, 2007), and an innovation system is defined as interdependent micro-elements (companies and the internal processes of the company and the interaction of companies and knowledge institutions) and macro-elements (the spatial scale in the context of education, markets, and regimes, and relations to other innovation networks) (Lundvall, 2007). The process of change is related to innovation as a source of dynamics (Freeman, 1988b; Lundvall, 2007). IS theory describes changes in the system through a cycle. The system will be at equilibrium when organizations, technology, and problem-solving follow the same pattern, that is, the same technological paradigm, but this is then interrupted by deviant behavior, driven by changes in both macro- and micro-elements throughout the system, and it may cumulatively result in a new equilibrium (Dosi, 1988; Dosi and Orsenigo, 1988). The entire process can be characterized as evolutionary equilibrium (Dosi and Orsenigo, 1988); therefore, no optimal solution exists, only 'temporary' equilibriums.

We focus on the city as the scale of innovation, by investigating a city innovation system (CIS). The argument for doing so resonates with regional innovation systems (Bunnell and Coe, 2001), in that cities are like regions nexuses of interaction with high concentrations of material and immaterial resources. Whereas IS research focuses traditionally on companies and knowledge institutions as core innovators, the CIS perspective highlights how other actors may be important in this regard, such as local authorities and service providers (public, semi-public, and private). Relevant to this focus on the city scale are recent discussions on the use of spatial scales in system change theories that have been especially prominent in transition science, which is a parallel strand of theory to innovation systems theory that studies the change of socio-technical systems into more sustainable modes (Markard and Truffer, 2008). In transition science, the main criticism has been the indirect use of space (Truffer et al., 2015; Truffer and Coenen, 2012). Most transition analyses focus on the national level, therefore implicitly assuming that transitions unfold and can be compared at the national level (Lawhon and Murphy, 2012; Monstadt, 2009; Truffer et al., 2015; Truffer and Coenen, 2012). Innovation system theory is criticized for applying space as a predefined, convenient way of distinguishing structure (Coenen et al., 2012; Lundvall, 2007), thereby neglecting the multi-scalar perspectives of innovation processes (Bunnell and Coe, 2001; Coenen et al., 2012). The debate in transition science has developed to the point where research includes an analysis of not only temporal and structural scales, but also spatial scales (Raven et al., 2012; Truffer et al., 2015), albeit still considering space relationally bound, i.e. system delimitations are abstract and often in accordance with the actor network and physical boundaries. Nevertheless, more recently, the concept of urban transitions has developed somewhat, to the extent that the spatial scale is the city, including relations with other especially governance scales (Frantzeskaki et al., 2017; Hodson et al., 2017; Krellenberg et al., 2016; Wolfram et al., 2016).

As described above, most research on the understanding of climate change adaptation is found in political science studies on policy effects or recommendations. By applying an IS perspective, this paper highlights the effect of actors on system change and feeds into the establishment of the emerging field of CIS research.

3. Methods

Our study's methods include several steps: a qualitative research design, a case selection strategy, interconnected data collection and analysis, and a process of validation encompassing the entire study.

3.1. Research design

We took a qualitative approach to further the understanding of different types of actors' perceptions of climate change adaptation and the implications of these perceptions for innovation. Through the qualitative approach, we sought detailed data on the CIS, involving multiple actors and institutions, resulting in multiple meanings and technologies (Bryman, 2012; Flyvbjerg, 2006; Yin, 2013). The main case, Copenhagen, was chosen because it is an unusual innovation system, in that the city's size and density increase the effects of climate change, and at the same time, the size of the system sets special requirements for innovation. In addition, internationally, there are multiple medium-sized (1-5 million people) cities like Copenhagen, thus making the case internationally relevant.

The research design is described in Figure 1. An initial theoretical literature study was done to provide a basis for the interviews. Case-relevant literature was collected continuously throughout the study, providing up-to-date and specific data such as reports (Jensen et al., 2016; Lund, 2016; Smith Innovation, 2015), books (Hoffmann et al., 2015), public plans (Københavns Kommune, 2012, 2011), and laws and acts (Regeringen, 2016). An early screening of the actor network was conducted together with three informants, who can all be considered front-runners in climate change adaptation. Interviews were conducted in two rounds. The first round's purpose was to identify the context—central characteristics of technologies, actors and institutions in the CIS—and included eight semi-structured, in-depth interviews with key actors alongside the following interview question categories: background; regime technologies; alternative technologies; internal innovation strategies; external innovation strategies; and Copenhagen. The second round aimed at investigating the day-to-day processes of innovation and implementation in climate change adaptation by focusing on three embedded, specific innovation case stories and the surrounding actors. Analysis was done through semi-structured, in-depth interviews with the relevant actors and resulted in 24 interviews with the following categories: background; climate change adaptation; actors; and innovation.

We propose an analytical framework based on the entire research design; however, an initial version emerged as a result of the inductive coding of the context interviews (Figure 1) and was then refined through the following data collection and analysis through the case of Copenhagen. Our framework outlines three main attributes that characterize climate change adaptation:

- Event magnitude. To what magnitude is the adaptation designed?
- Spatial scale. At what scale should climate change adaptation work?
- Goals. What are the goals of climate change adaptation?

We propose that how actors conceptualize the combination of these three attributes, i.e. event magnitudes, spatial scales, and goals, may result in different choices of technology.

Figure 1: Research design structure of the study, with [R1] and [R2] referring to rounds 1 and 2 of the data collection and analysis.

3.2. Case selection

The strategies used to choose the case differed between the main paradigm of Copenhagen and the embedded cases of innovation.. The extreme case of Copenhagen guides the generalizability of the study, in that what is true for extreme cases can be found true in other cases (Flyvbjerg, 2006; Neergaard and Ulhøi, 2007; Yin, 2013).. Innovation stories were chosen based on the maximum variation criteria (Figure 1), to illustrate the main case through the different municipality-utility relationships, which proved to be a key innovation factor for both the development and diffusion process. Choosing cases varying in relation to certain key factors will show variations in the research topic and allow patterns to emerge (Neergaard and Ulhøi, 2007).

3.3. Case context

Copenhagen is the capital city of Denmark and is located by the Oresund strait in Northern Europe. The urban area studied here geographically covers the Greater Copenhagen area, which is the most densely populated area in Denmark, with 1.3 million people (Statistics Denmark, 2017). It consists of several municipalities, with the City of Copenhagen (including the much smaller municipality Frederiksberg) covering central parts of the urban spread. In Copenhagen, climate change adaptation is linked closely to stormwater management (Københavns Kommune, 2011) because of previously experienced pluvial flood events. The legal framework is the existing Water Sector Law (Regeringen, 2009), which sets out the main actors' responsibilities and their economic relationship. Water utilities in Denmark are private companies owned by municipalities, and they supply water, drainage, and/or wastewater services to customers under the economic authority of the Danish Consumer and Competition Agency. The municipality as the public authority sets service levels for the urban stormwater system that the utility supplies.

Innovation cases in the second data collection round were (1) the implementation of climate change adaptation on private property, (2) the Cloudburst Valve (in Danish *Skybrudsventilen*), and (3) climate change adaptation with the Nordvand Utility (Table 1). Case 1 involves process innovation, whereby three companies proposed a business model for facilitating the implementation of climate change adaptation on private property in the City of Copenhagen through the Co-financing Act (Regeringen, 2016), which allows utilities to finance climate change adaptation by raising water tariffs. Case 2 represents product innovation, whereby a small start-up company developed a product, namely the Cloudburst Valve, which decouples stormwater from downspouts during cloudbursts and thus prevents stormwater from entering the combined sewer system. Case 3 shows how inventions diffuse onto the market, thus showing how a utility company in the Greater Copenhagen area, Nordvand Utility, has applied new technologies and processes throughout their implementation of climate change adaptation.

Table 1. Innovation cases for study: Type of case, utility company, municipality, and project owner involved in the case.

3.4. Data collection and analysis

The interviewees in the context round were selected from an initial screening of the actor network (Figure 1) based on three informants. The interviewees were then chosen against intensity and maximum variation criteria, which are applied for information-rich and varying cases, respectively (Creswell, 2013). They were chosen to reflect different actor types and individuals with a high degree of power, involvement in innovation, and knowledge of the actor network and technologies (Table 2), in order to cover different and important context elements, and to make sure subsequent data collection information needs were covered (Figure 1). The interviewees in the second round were selected based on the snowball criterion, in which an interviewee's mentions of other actors determine the selection (Creswell, 2013). This allowed us to map the full network of actors surrounding the innovation cases and their relations to each other. The point of saturation in this case occurred when no new actor was mentioned by the interviewees, or if no new relevant knowledge was obtained in the interviews.

Table 2: Interviews divided among actor types.

The interviews were analyzed in the computer-assisted qualitative analysis (CAQDAS) software ATLAS.ti (Knopasek, 2008), which allowed for structured data analysis and assisted in interpretation and validation (Knopasek, 2008; Seale, 2013). First, the interviews were recorded and transcribed, following which they were coded by aggregating the text into thematic categories (Creswell, 2013), using a mixture of deductive and inductive coding. The codes were deduced from CIS theory and induced from the transcriptions of the first data collection round; see the coding list in Supplementary Information SI 1. The coding was therefore done in cycles, first by going through each interview once and coding with all families, and then coding once for each family.

A pattern of results emerged from the coding and the following interpretation of data. The translation of Danish into English happened afterwards, in the dissemination of the results, and the translation of words of the field are reported in Supplementary Information SI 2. The case-specific literature became part of the analysis at this point, as opposed to the theoretical literature, which informed the entire research design (Figure 1). The coding resulted in 500 different individual conceptualizations of climate change adaptation, that is, different mentions of one or more event magnitudes and/or spatial scales and/or goals and/or technologies. We coded a total of 116 mentions of event magnitude, 215 mentions of spatial scale, and 645 mentions of goals. The numbers following conceptualizations in the text represent the amount of mentions.

3.5. Validation

One of the main perceived weaknesses of a qualitative approach is researcher bias (Bryman, 2012), which this study aimed at reducing through internal and external validity (Yin, 2013). The study applied several sources of data to build construct validity: informants, two separate interview rounds, three separate embedded cases and additional context interviews, as well as supplementary academic and non-academic literature. This allowed several opportunities for triangulating results (Yin, 2013). Reliability was strengthened through the chain of evidence (Yin, 2013), which was kept throughout the data collection process with the use of an interview log, transcripts, coded transcripts, CAQDAS software, and a method log. To strengthen internal validity, the study addressed rival explanations in the data analysis by allowing informants to validate results, providing interviewees with an opportunity to correct and supplement the interview in the summary given at the end of the session, and allowing key interviewees an opportunity to comment on the manuscript. External validity was strengthened by CIS theory from the outset by using interview guides, coding schemes, and analysis.

4. Results

4.1. Overall compilation of the interview data

Table 3 shows a word count for all interviews; common words are excluded to show only those words describing the field of climate change adaptation. A bricolage of words and definitions appears when comparing the practitioners' word use. Words describing a technical solution or a problem to solve are common, such as "the soil", "pipe/pipes" and "cloudburst" and yet more frequent are process-describing words such as "solution", "relationship/conditions" and "network" as well as mentions of actors such as "municipality", "consultant" and "utility". The definition of climate change adaptation clearly includes numerous aspects, and so a short definition cannot be given. We therefore continue the analysis by using the "event magnitude–spatial scale–goals" framework, supplemented by technology choices as defined in section 3.1.

Table 3: Count of field descriptive words mentioned at least 50 times in the interviews and translated into English. Additionally, names are excluded from the list. * = inflections of words combined.

4.1.1. Event magnitude

The terminology of the 3PA seems to have diffused into practice, since different actors refer to the 'everyday', 'design', and 'extreme' domains when talking about event magnitudes. This becomes clear when characterizing the conceptualizations of event magnitudes according to the two variables' return periods (that is, the reciprocal of the frequency of a rain event occurring based on historical data) and event depth (that is, the total amount of rainfall in an event). A pattern appears (Figure 2) showing that the everyday domain is rarely mentioned (5/116) and seldom in association with a return period. The design domain (47/116) is quantified or termed as "normal rain" or "service levels". The design domain and everyday domain are also mentioned as one entity, called "not cloudburst"; these conceptualizations are shown in Figure 2 in the design domain. The most-mentioned domain is the extreme domain (64/116), which is both quantified to a return period of T=100 years and mentioned as "cloudburst". The domain is also called a range of other things, for example, "large rain events", "extreme rain", "heavy rain" or "chaos", reflecting that it is the main focus of the actors. Three interrelated actors mentioned the "level of security" as comparable to "service levels" defined in the design domain, while three other distinct actors also mentioned that climate change adaptation considers a "range of events" (Figure 2). Besides a quantitative increase in conceptualizations towards the extreme domain, Figure 2 also shows an increase in diversity towards the extreme domain. Diversity in conceptualizations is greatest in the extreme domain.

Figure 2: Conceptualizations of event magnitudes (return period and event depth) for all actor types, organized according to the 3PA domains: Everyday domain (day-to-day values), design domain (technical optimization) and extreme domain (urban resilience).

4.1.2. Spatial scale

The actors' conceptualizations of climate change adaptation can also be divided into different spatial scale categories: Large (international and national), medium (urban), and small (local) (Figure 3). Few actors (19/215) mentioned the larger spatial scales, which contain general scales such as "society" and "overall solution" as well as specific scales such as "international", "national" and "region". The medium spatial scales are centered on the city and the administration of its infrastructure, for example "municipality", "utility", "water catchment", and "sewage system". It is worth mentioning that the term "water catchment" includes a range of different catchment types, which the actors rarely distinguish, e.g. groundwater, sewage, and surface runoff catchment. The smaller spatial scales were mentioned together with specific projects, for example "neighborhood", "homeowners' association", "road" and "cadaster". In a few interviews, different scales were mentioned together; specifically, "utility" versus "cadaster" were often mentioned together as opposites, as these scales have different financing and implementation processes. The medium and small spatial scales were mentioned most often (respectively 120/215 and 76/215), reflecting that most actors had a natural focus on projects within a given area of a defined size.

Figure 3: Conceptualizations of spatial scales for all actor types, organized in three levels: Large (international/national), medium (urban), and small (local).

4.1.3. Goals

Climate change adaptation goals mentioned by the actors varied greatly, and a goal was always mentioned in connection with other goals or with an event magnitude, spatial scale, or technology; therefore, it does not stand alone and should be considered in its context. Table 4 lists the conceptualized goals in ten overall categories: innovation; urban; water quantity; water quality; nature; economic; health and safety; social; aesthetic expression; and multifunctional. Prominent goals include “reduce cost” (101/645), “prevent flooding damages” (40/645), “better water quality” (24/645), and “reduce volume in sewage” (23/645). Frequent combinations of goal categories include economic and water quantity (focusing on reducing the cost of floods and the management of water volumes), and aesthetic expression, social, and urban (focusing on creating the visibility of climate change adaptation in an active urban space for all actors). Economic goals are always combined with other categories in reference to cost-benefit analyses. Similarly, goals with reference to multifunctionality are always directly combined with a range of other goals or indirectly with reference to cost-benefit analyses.

Table 4: Example of goals from all interviews reduced in summarizing categories.

4.1.4. Technology choices

Figure 4 shows how the different technologies mentioned by the interviewees are located throughout the urban water system. For a full list of technologies, see Supplementary Information SI 3. The actors’ choice of technologies when innovating or implementing climate change adaptation encompasses the whole urban water cycle. Additionally, the choice of technologies can be categorized as a combination of above- or below-ground solutions, the latter of which include separated or combined sewers, tunnels and pipes, and basins, while above-ground solutions include LAR (often also even if they are not above-ground solutions, as we see, for example, with some infiltration measures), cloudburst detention and transport, and a range of green solutions. The interviewees also call below-ground solutions traditional solutions and above-ground solutions alternative solutions, with reference to the Co-financing Act’s definition (Regeringen, 2016). The choice of technologies seems to depend on the innovation or implementation projects’ targeted event magnitudes, spatial scales, and goals. However, above-ground solutions are often prioritized, especially to accommodate multifunctionality and cost reduction goals, again with reference to cost-benefit analyses.

Figure 4. Locations (white boxes) of technologies in the urban water system (grey boxes) mentioned across the interviews.

4.2. Definitions from the main case

Table 5 shows the primary narratives of climate change adaptation definitions for all eight context interviewees. There is no single definition of climate change adaptation, but several combinations of event magnitudes, spatial scales and goals in association with specific technologies prevail. The actors, however, combine these three attributes to match their specific project, resulting in inconsistent definitions. These variations in definitions are often connected to the actor's education and previous work in addition to their current work. The engineering consultant, municipality, and utility actors mostly work within the design domain and extreme domain with regard to event magnitudes, they design for the medium spatial scale, and they focus primarily on economic and water quantity goals. However, the utility actors also focus on innovation goals, while municipality actors focus on water quality goals, aesthetic expression goals, and social goals. This stands in contrast to actors from consultancies outside engineering, who work primarily within the extreme domain and with greatly varying goals, albeit with less focus on economic goals than most other actor types. It is also worth noting that other governmental actors besides municipal actors have a wider focus with regards to event magnitudes, goals, and spatial scales, as they concentrate on a range of event magnitudes, economic goals in the form of job creation and cost reduction, and designs for regional or societal scales. Furthermore, producers seem to focus on the small spatial scale when innovating climate change adaptation. The overall current primary definition of climate change adaptation in Copenhagen among practitioners is the linking of above-ground and below-ground cloudburst solutions (event magnitude: extreme) within a surface water catchment system (spatial scale: medium), designed to both prevent damage and generate day-to-day values for citizens (goal: cost, multifunctional). Even though there are correlating tendencies in the actors' definitions of climate change adaptation, individual actors' definitions vary greatly in relation to the individual innovation or implementation project. This is reflected in variations in event magnitudes, spatial scales, and goals (Figure 2, Figure 3, Table 4, and Figure 4), but it is also seen in specific goals aimed at seeking locally adapted solutions developed together with citizens or other actors, aiming for visibility, synergy, and integration with other infrastructure.

Table 5. Primary narratives of climate change adaptation definitions for eight context interviews, organized according to actor type, event magnitude, spatial scale, and goal.

4.3. Definitions of innovation case stories

Climate change adaptation innovation and implementation is affected by the broad and varying definition of a diverse range of technologies. This can be illustrated through the narratives of the study's three innovation cases, where different conflicts arose because of varying actor definitions and mismatching regulations.

4.3.1. Case 1 – Process innovation

In case 1, an innovation for implementing climate change adaptation on private property through the use of the Co-financing Act (Regeringen, 2016), the innovation process was affected severely by a multitude of actors' varying definitions (Table 6). The utility and consultancies in the case did not agree on the definition and did not see the same premises for the projects. This was a main reason, though not the only one, why process innovation failed, as no co-financing projects were implemented. The utility company is the coordinating actor in co-financing projects, as it facilitates private applications for regulating authorities and the municipality. In this case, the utility defined climate change adaptation projects on privately owned public roads as an adaptation to a design domain (T=2), with water quantity as the economic goal, designing for the medium spatial scale. This stands in contrast to one of the consultancies wanting to facilitate private homeowners' association projects. The consultancies focused on the design and extreme domain with regard to event magnitude, designing especially for the small spatial scale (homeowners' associations) and including a larger range of goals, along with water quality. Several of the case actors, including the utility, pointed to these differences in the project premises in the interviews as one reason for project failure.

Table 6. Primary narratives of climate change adaptation definitions for interviews related to case 1, organized according to actor type, event, scale, and goal.

4.3.2. Case 2 – Product innovation

In case 2, the innovation of the new Cloudburst Valve product, members of the small development team, consisting of two consultants and a production company, had very similar definitions of climate change adaptation. Their product will function in the cloudburst domain for the small (cadaster) and medium (utility) spatial scales, alongside economic and water quantity goals (Table 7). The internal development process therefore went relatively smoothly, aiming at a market where the utility company would buy their product for installation on private property. Challenges arose when considering existing regulations. Danish law does not allow utility companies to directly finance climate change adaptation on private property, but an opportunity in this regard exists in two alternative ways through the Co-financing Act and through a refunding the connection fee. The Co-financing Act is not suitable for low-cost projects such as the

Cloudburst Valve, while refunding the connection fee requires the full decoupling of stormwater for all event magnitudes, which Cloudburst does only for extreme rain events. The Cloudburst Valve as a climate change adaptation measure differs from existing regulatory institutions' definitions of climate change adaptation with regard to spatial scale (cadaster and utility) and event magnitude (only extreme domain) and can therefore not be implemented easily under existing regulations.

Table 7. Primary narratives of climate change adaptation definitions for interviews related to case 2, organized according to actor type, event, scale, and goal.

4.3.3. Case 3 – Diffusion of innovation

In case 3, namely the implementation of climate change adaptation by Nordvand Utility, the current picture is a stable definition of climate change adaptation. Utility and collaborating actors, corresponding municipalities, and engaged engineering consultants share this definition. Climate change adaptation functions at the design and extreme domains (quantified to T=5/10 and T=100), designed for the medium spatial scale (water catchment) with a varying set of goals (Table 8). However, looking from the temporal perspective, the case tells a story of how this definition was developed. First, it was realized in a specific implementation project whereby designing for the water catchment scale results in large cost reductions for the utility and the municipality. The next step was the integration of social goals, valuing extensive actors, and especially citizen participation. This led to the current development, where the quantification of the extreme event magnitude is re-evaluated with regard to the specific goal of creating a societal cost-benefit, namely the level of security. In this case, the climate change adaptation definition is developed through the utility's implementation projects. However, throughout the development process, the utility company has openly expressed and reflected on the definition while sharing lessons learned with close actors (municipality and engineering consultant) and other actors, inviting the public for tours of their projects. The utility has also stressed in interviews that sharing and reflection processes can be sensitive and resource-consuming.

Table 8. Primary narratives of climate change adaptation definitions for interviews related to case 3, organized according to actor type, event, scale, and goal.

5. Discussion

5.1. Event magnitude, spatial scale, and goals as the main characterizing attributes

Our empirical work validates our analytical framework, showing that, in practice, event magnitude, spatial scale, and goals are characterizing attributes of climate change adaptation. The event magnitude attribute is supported by the "adaptation to what" question previously proposed by Smit et al. (2000), while spatial scale as an attribute is highlighted in several places in the literature (Biagini et al., 2014; Smit et al., 2000) and connected to both the choice of technology and to the involved actors (Smit et al., 2000). This study shows that the opposite relationship between actors and spatial scale is also present, in that involved actors define the spatial scale of the adaptation collectively. It highlights furthermore that the choice of technology is also connected to event magnitude and goals. Finally, the multitude of goals and involved technologies, also described as characterizing attributes in this study, is supported by previous studies' similar conclusions (Biagini et al., 2014). Previously, these manifold goals, technologies, and other adaptation measures have been mixed together in the typology of climate change adaptation (Biagini et al., 2014), but herein we separate the attributes goal and technologies, as climate change adaptation involves a choice of both a goal and technology.

Event magnitudes applied by the actors can be arranged into the three domains from the 3PA (Fratini et al., 2012), confirming that the domain structure and terminology of the 3PA is used in practice. However, the actors do not describe or quantify the domains exactly as defined in the scientific literature (Fratini et al., 2012; Sørup et al., 2016), instead, they apply their individual definitions and quantifications, with some, for example, defining a 0.5-year return period as a cloudburst and the extreme domain, which is a misconception from a hydrological scientific standpoint. Furthermore, the actors have not adapted the main proposition of the 3PA, namely that stormwater management should ideally consider all three domains in an integrated manner; rather, the domain used most is the extreme domain, conceptualized with "cloudburst" and quantified as "T=100". Often, the other domains, i.e. day-to-day and design, are conceptualized as "not cloudburst", showing that even though the 3PA structure and terminology are applied in practice, the interface between the domains is perhaps more blurred. Other researchers have presented an additional "no-recover" domain with events from which the system cannot recover, thus increasing the total number of domains from three to four (Digman et al., 2014; Gersonius et al., 2016), though our interviews do not find evidence of this concept being referred to in practice.

Actors' conceptualizations of the spatial scale of climate change adaptation can also be organized into three categories: Large (national/international), medium (urban), and small (local). The medium and small scales are the most frequently mentioned spatial scales throughout our interviews. This focus on the small and medium scales can be explained through the existing institutional framework for stormwater management, which is the urban scale. However, as with event magnitudes, in order to receive all adaptation benefits, it is wise to consider all three spatial scales when innovating and implementing climate change adaptation (Demuzere et al., 2014).

The goals of climate change adaptations vary greatly among actors, which is in line with previous work, for example "Water Aspects" (Fratini et al., 2012; Geldof, 2005). Prominent among these are economic goals, water quality goals, and water quantity goals, though economic and multifunctional goals are often mentioned in line with a range of others with reference to cost-benefit analyses. This cost-benefit is not specific; rather, it is a cognitive institution, a belief taken for given. This large variation in goals reflects the multidisciplinary character of climate adaption, and the focus on economic goals and multifunctionality can be considered the main cognitive paradigm for practitioners working with climate change adaptation in Copenhagen.

General combinations of event magnitudes, spatial scales, goals, and technology choices characterizing climate change adaptation do not exist in our interview data, which differs from previous work based on scientific rigor, where these elements have been linked (Fratini et al., 2012; Sørup et al., 2016). Moreover, our study does not contradict previous studies, as it shows how actors apply these definitions in practice, while previous studies have focused on developing a general communication model.

With regard to variations among specific actor types, different clusters of actors may be proposed. The engineering consultant, the municipality, and the utility, i.e. the three classic collaborating actors in stormwater management, share a common focus on the design and extreme domain with regard to event magnitudes, and a focus on the medium spatial scale, and have primarily economic and water quantity goals. With the climate change adaptation field being new, several new actors are getting more involved, and other consultants specializing in, for example, process facilitation or architectural design are now becoming more central actors that introduce a larger variety of new goals. The variety in combinations of categories and the tendency of actor types to converge reflects the interdisciplinary character of climate change adaptation.

5.2. Implications for innovation and implementation

A lack of consensus presents a possibility for conflict, which becomes especially visible in the implementation of climate change adaptation, but it is also present in knowledge-sharing and knowledge-developing activities, as exemplified in Cases 1 and 2. Case 1 is an example where ambiguous conflicting definitions severely affect the innovation and implementation process. The Co-financing Act has since our interviews been abandoned as a way of financing climate change adaptation on private property in the City of Copenhagen. Case 2 is an example of how regulative institutions do not match actors' definitions of climate change adaptation. Similar examples of mismatching regulative institutions have previously been reported (e.g. Lund, 2016), and although our analysis shows an emerging cognitive paradigm, where economic goals and multifunctionality are linked with cost-benefit analyses for adapting to extreme rain events on a water catchment scale, regulative institutions do not yet match this change. A systemic change has therefore not emerged, as a full paradigm shift requires cognitive, normative, and regulative institutions (Nelson, 1995, 1994). However, when there is no clear definition of climate change adaptation, there is an environment that offers opportunities for innovation. Case 3 is an example of how the continuous expression and discussion of a climate change adaptation definition can result in innovation and implementation and the mainstreaming of new technology. However, the case also exemplifies that the process is not easy and requires many resources.

Our research design, with interconnected data collection and analysis rounds, strengthens the interpretation and analysis of qualitative data by allowing opportunities for validation. To strengthen the framework further, the findings of this study could be elaborated further and tested on more case studies at other locations, with different climates and socio-technical institutions.

6. Conclusion

This paper investigates how the understanding of climate change adaptation varies across core actors in the city innovation system (CIS) and how this influences the innovation and implementation process. We propose an analytical frame for characterizing climate change adaptation according to three attributes: event magnitude (everyday, design, and extreme), spatial scale (small/local, medium/urban, and large/national-international), and (a wide range of) goals. We outline a comprehensive and inclusive framework for the practical definition of climate change adaptation, supported by our empirical work exemplifying the case of pluvial flooding in Copenhagen.

Our interview data show that the general definition of climate change adaptation in Copenhagen currently remains diffuse among actors, who do not agree on what it means and their choices of different attributes result in different choices of technologies. These actors apply their individual definitions of event magnitude and prioritize the extreme domain. Regarding space, there is a strong focus on the medium and small scales (urban and local), with very few actors mentioning the larger spatial scale (national/international). The goals of climate change adaptation furthermore vary greatly among actors, with specific goals always mentioned along with other goals or event magnitude, spatial scale, or technology. However, these actors most frequently mention cost reduction as a goal, referencing cost-benefit analyses as a cognitive belief institution. Their choice of technology involves the entire urban water system, and it can be characterized as either an above- or a below-ground solution. Often, above-ground solutions are prioritized with reference to cost-benefit analyses. Currently, there is convergence among actors toward a new cognitive paradigm, whereby economic goals and multifunctionality are linked with cost-benefit analyses for adapting to extreme rain events on a surface water catchment scale. However, the current regulative institutions do not match this change in cognitive paradigm, and so systemic change has yet to happen.

Differences in definitions can lead to both opportunities for innovation and to conflicts affecting the innovation of climate change adaptation. Many interpretations and clear expressions and discussions of definitions can result in innovation and the partial mainstreaming of new technology, though a lack of consensus can also lead to conflict in both innovation and implementation. The ambiguous definition indicates that climate change adaptation is a new development in the field of stormwater management, where the previous paradigm was formulated more than 100 years ago, and this ambiguity in the definition affects the city's capacity for change. Nevertheless, the field is experiencing rapid ongoing development and has gained a great deal of momentum, leading to new technologies, processes, and implementation projects that may eventually lead to major innovations on the city scale. Our study shows that if those actors working together express and reflect on their work, the diversity in the definition will enable successful innovation and implementation. We therefore recommend that the project owner of specific innovation and implementation projects incorporates discussions on the definition of climate change adaptation in their projects. This is relevant for both municipalities and utilities as project owners in implementation projects, and private companies and knowledge institutions in innovation projects. Furthermore, we recommend that further work concentrates on developing and communicating a clear and inclusive definition of climate change adaptation, including the attributes event magnitude, spatial scale, and goals as important factors that may potentially determine the choice of technology.

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Table 1. Innovation cases for study: type of case, and utility company, municipality and project owner involved with the case.

Case description			Utility company	Municipality	Private Companies
Case 1	Implementation of climate change adaptation on private property	Process innovation	HOFOR: Greater Copenhagen Utility	City of Copenhagen	Klimavej ApS MT Højgaard A/S PKP Regnvandsteknik ApS
Case 2	The Cloudburst Valve	Product Innovation	Tårnby Utility	Tårnby Municipality	Vandvenderne ApS Plastmo A/S
Case 3	Climate change adaptation with Nordvand Utility	Diffusion	Nordvand Utility	Gentofte Municipality Gladsaxe Municipality	[several hired engineering consultancies]

Table 2: Interviews divided among actor types.

Actor type	Description	Context	Case1	Case2	Case3
Construction	works in a construction company	-	1	-	-
Engineering Consultant	works in a primarily engineering consultancy	1	3	1	3
Municipality	works in a municipality	1	1	-	2
NGO	works in a non-governmental organization	1	-	-	-
Other Consultant	works in a consultancy which is not primarily engineering	2	1	2	-
Other Governmental	works in a governmental institution other than municipality	1	2	-	-
Production	works in a climate adaptation product company	1	-	1	-
Research	works at a research institution	-	-	2	-
Utility	work at a utility company	1	2	1	2
Total (32)		8	10	7	7

Table 3: Count of field descriptive words mentioned at least 50 times in the interviews and translated to English. Additionally, names are excluded from the list. * = inflections of words combined.

project* (640)	area (159)	job/assignment* (101)	the market (59)
municipality* (600)	private (158)	pipe/pipes (84)	level (58)
water* (572)	technical* (153)	rain (83)	secure (57)
solution* (527)	innovation (149)	the citizens (79)	denmark (56)
road* (388)	consultant* (148)	the surface (79)	agreement/contract (54)
copenhagen* (370)	utility* (135)	the soil (78)	existing (54)
city* (281)	network (130)	plan (75)	system (53)
relationships/conditions (332)	event* (114)	lar (68)	tender (53)
climate change adaptation (241)	green (105)	catchment (62)	environment (50)
cloudburst (180)	areas (103)	the sewage (59)	

Table 4: Example of goals from all interviews reduced in summarizing categories.

Innovation concerning the innovation process	**Urban** concerning the urban environment	**Water quantity** concerning management of water quantity	**Water quality** concerning management of water quality	**Nature** concerning the natural system
develop standards	active urban space	appropriate groundwater levels	better water quality	biodiversity
easy to implement	coordinated with other renovations	increase infiltration	potable water quality and quantity	ecosystem services
increase innovation	experiential	preserve water balance		environmental friendly
range of solution	integrated with other urban infrastructure	prevent basement flooding		increase nature
transferability	optimize for technical conditions	prevent droughts		reduce resource use
	optimize land use planning	prevent flooding damages		
	recreative value	prevent overflows		
	urban development	reduce peak loads		
		reduce volume in sewage		
		secure hydraulic capacity		
Health and safety concerning health and safety measures	**Economic** concerning economic aspects	**Social** concerning social measures	**Multifunctional** concerning more than one function	**Aesthetic expression** concerning the aesthetic expression
increase safety	best cost-benefit	actor participation	added value	avoid boring solutions
noise reduction	easy maintenance	better social environment	everyday function	increase visibility
prevent untimely death	economic growth	communication and marketing value	holistic solution	locally adapted
reduce air pollution	energy savings	global responsibility	integrated solutions	pleasing aesthetic
reduce urban heat island	green growth	intergenerational equity	multifunctional	quality
resilience	optimize marginal cost	liveability	sustainability	clean expression
robust	optimize water-energy balance	perfect timing	synergy	simple solution
	reduce cost	quality of life	systemic solution	unique characters
	reduce maintenance cost	respect culture		

Table 5. Primary narratives of definitions of climate change adaptation for eight context interviews, organized according to actor type, event magnitude, spatial scale and goal.

Context			
Actor type	**Event magnitude**	**Spatial scale**	**Goal**
Engineering consultant	T=10, cloudburst T=100	city	prevent flooding damages, reduce cost
Municipality	cloudburst, everyday	city, international	best cost-benefit, prevent flooding damages, develop standards, added everyday values
NGO		city	prevent flooding damages, prevent droughts, quality of life, resilience, integrated with infrastructure, citizen participation
Other consultant	large events, extreme rain	neighborhood, city	added value, locally adapted, systemic solution, more nature, more green
Other consultant	cloudburst, normal water volumes		prevent basement flooding, increase visibility, added values, technical simple
Other govern-mental	full range, T=10, large rain events	society	reduce cost, prevent flooding damages, secure hydraulic capacity, robust
Production	cloudburst	cadaster, road, city	prevent flooding damages, prevent basement flooding, function as transportation
Utility	T=10, cloudburst	water catchment	synergy with other infrastructure, reduce cost, prevent basement flooding, optimize land use planning, better water quality

Table 6. Primary narratives of definitions of climate change adaptation for interviews related to case 1, organized according to actor type, event, scale and goal.

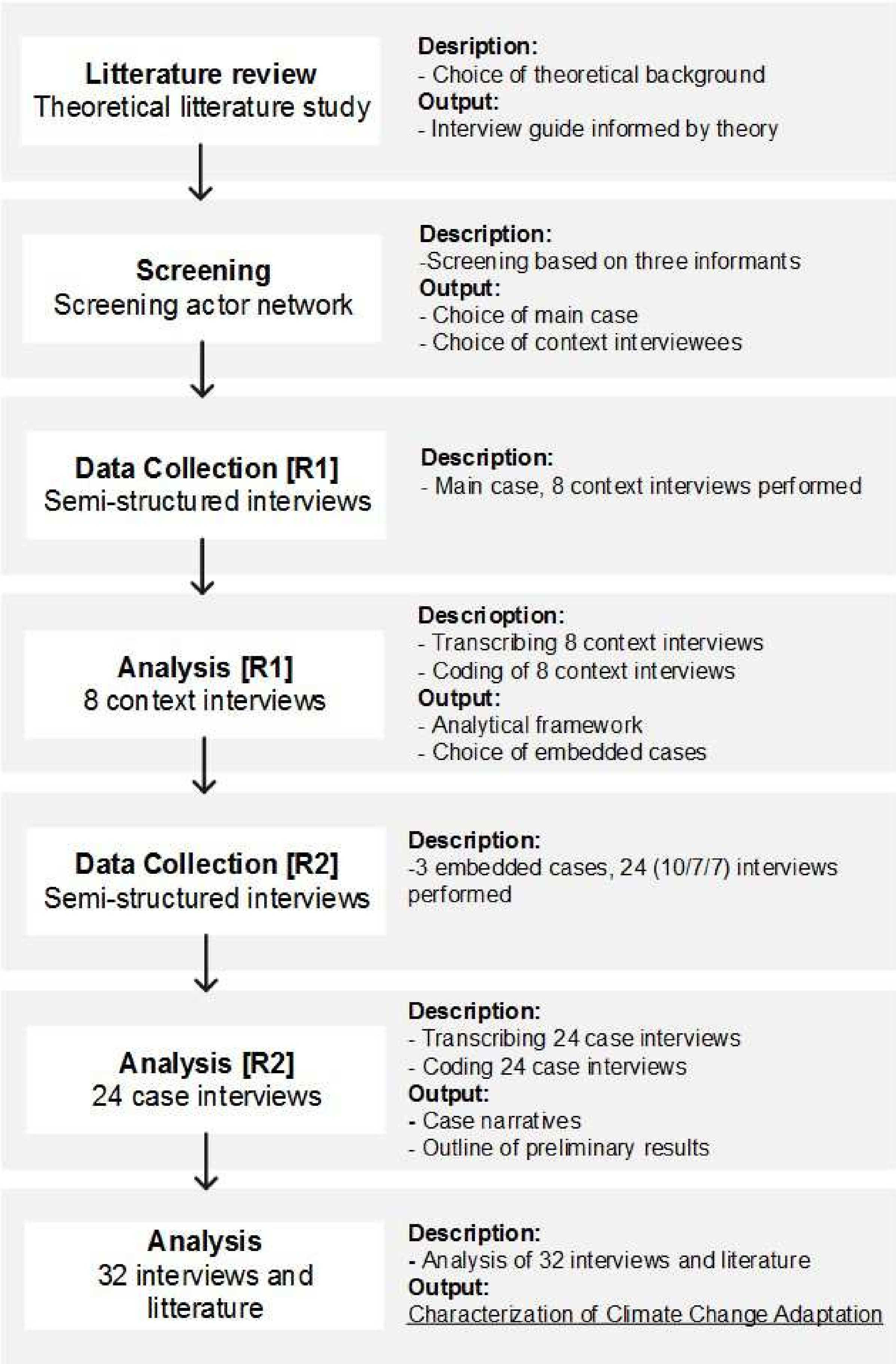
Case 1			
Actor type	**Event magnitude**	**Spatial scale**	**Goal**
Construction	T=5/10, cloudburst T=100	homeowner's association, utility	reduce cost, maintenance cost, develop standards solutions, prevent basement flooding
Engineering consultant	cloudburst, T=5-10	homeowner's association	prevent flooding damages, secure hydraulic capacity, reduce cost
Engineering consultant		utility, homeowner's association	reduce cost
Engineering consultant	normal events, cloudburst	utility, city, municipality	reduce cost, perfect timing, better water quality, good groundwater levels, reduce maintenance cost
Municipality	T=100, 10 cm water on terrain	city, water catchment	reduce cost, easy maintenance, integrated with infrastructure, added value, optimize marginal cost
Other consultant	everyday rain, service goals, T=5, cloudburst	homeowner's association, city	reduce cost, better water quality, easy maintenance, increase safety, reduce volume in sewage
Other govern-mental	service levels, T=100	utility, city, municipality, cadaster	optimize urban land use planning
Other govern-mental	range of events	region	prevent flooding damages, best cost-benefit, economic growth, job creation
Utility	T=2, cloudburst	municipality, water catchment	reduce cost, prevent flooding, better water quality, added values, quality of life
Utility	cloudburst, T=2	city, homeowner's association	reduce volume in sewage, reduce cost, prevent basement flooding

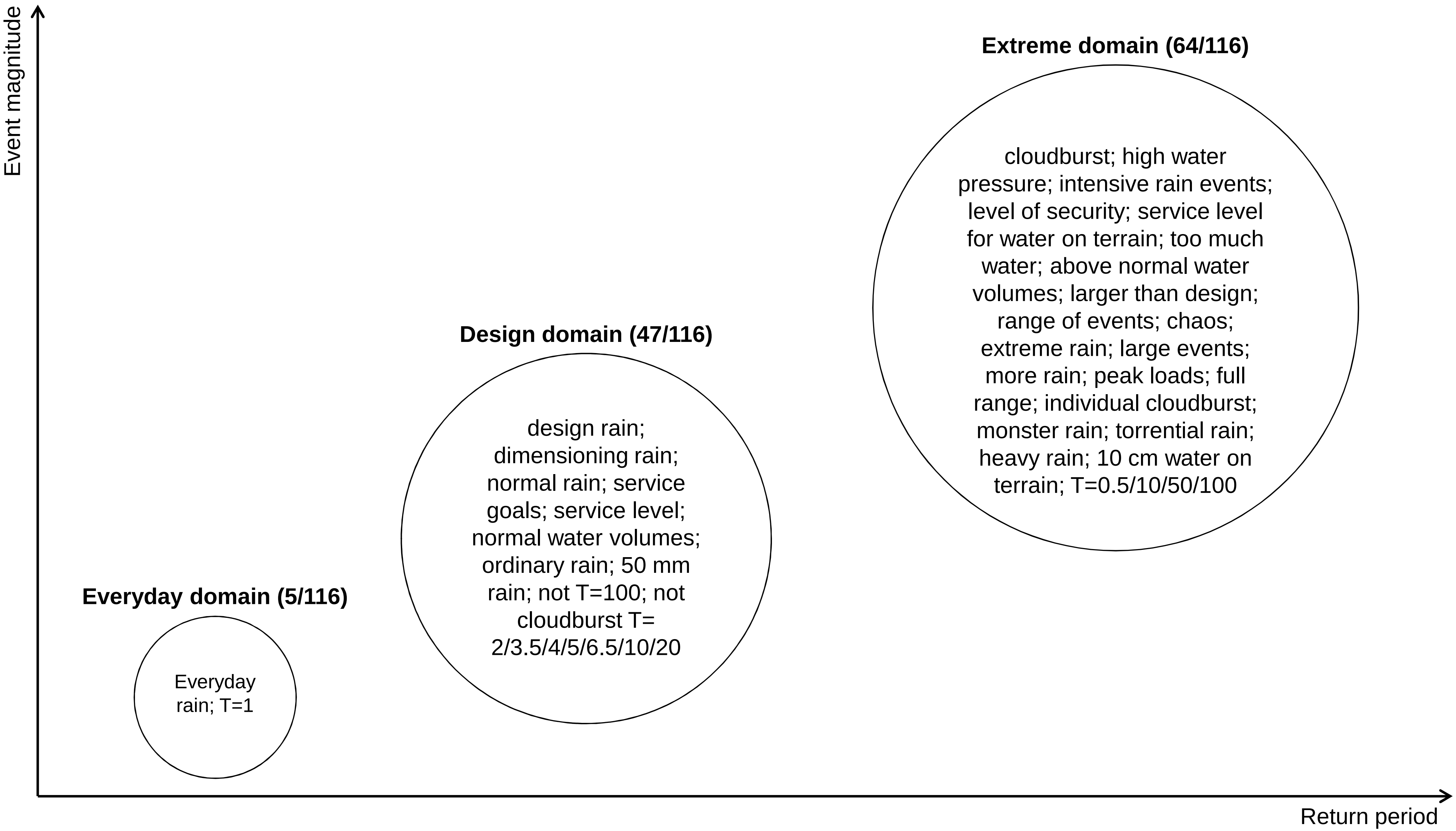
Table 7. Primary narratives of definitions of climate change adaptation for interviews related to case 2, organized according to actor type, event, scale and goal.

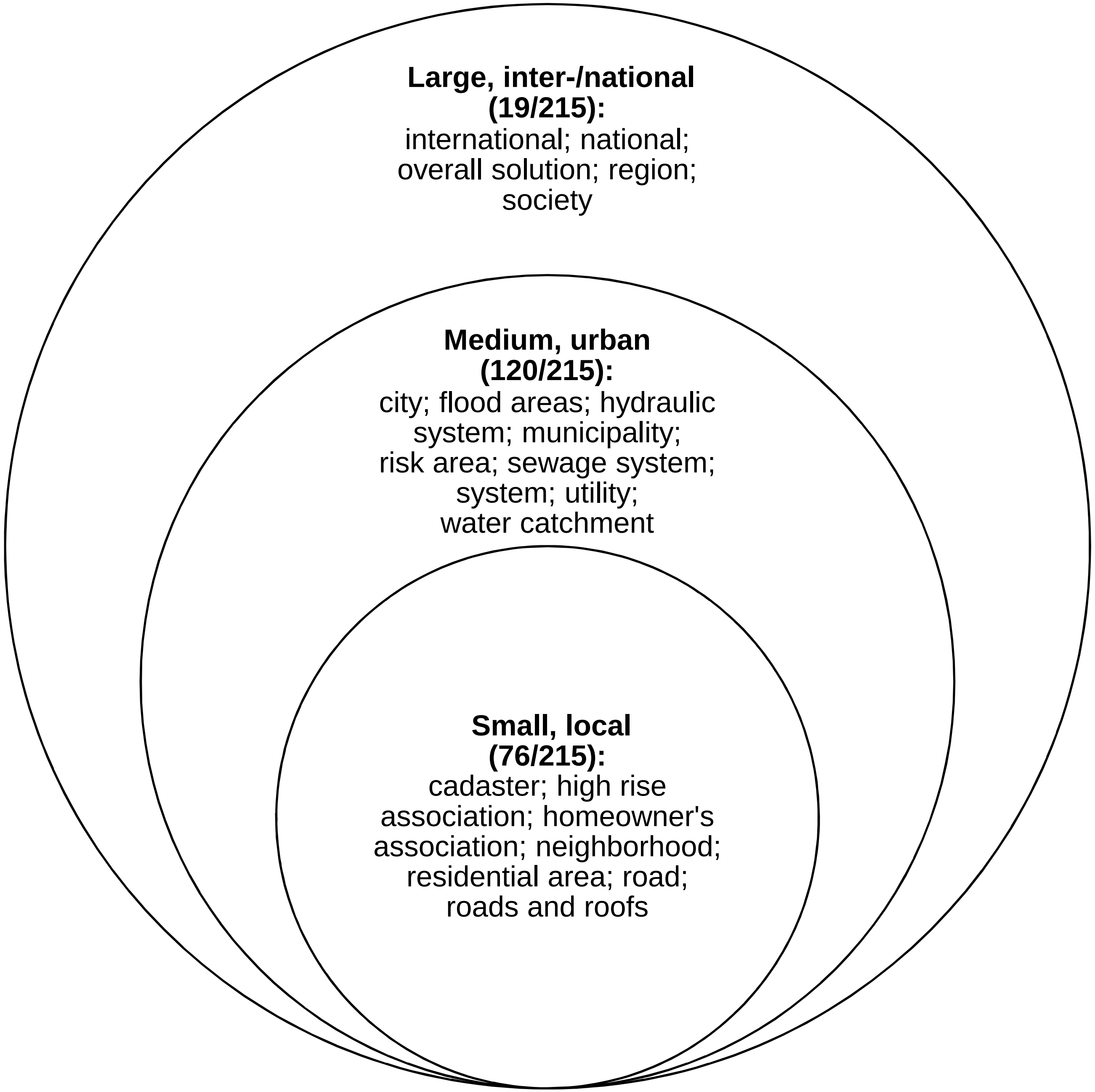
Case 2			
Actor type	**Event magnitude**	**Spatial scale**	**Goal**
Engineering consultant	everyday rain	sewage system	reduce cost, prevent flooding damages, prevent basement flooding, reduce maintenance cost, quick fix, appropriate groundwater levels
Other consultant	cloudburst	cadaster, utility	reduce volume in sewage, prevent basement flooding
Other consultant	dimensioning rain event, more rain	society, cadaster	increase visibility, transferability, integrated with infrastructure, reduce cost, systemic solution
Production	cloudburst, normal rain	cadaster, homeowner's association	reduce volume in sewage, reduce cost, easy to implement
Research	torrential rain, ordinary rain	cadaster	prevent flooding damages, simple mechanical solution
Research	cloudburst T=100	cadaster	prevent flooding damages, recreative value, optimize urban land use planning
Utility	normal rain, cloudburst	utility	reduce cost, reduce resource use, simple solution

Table 8. Primary narratives of definitions of climate change adaptation for interviews related to case 3, organized according to actor type, event, scale and goal.

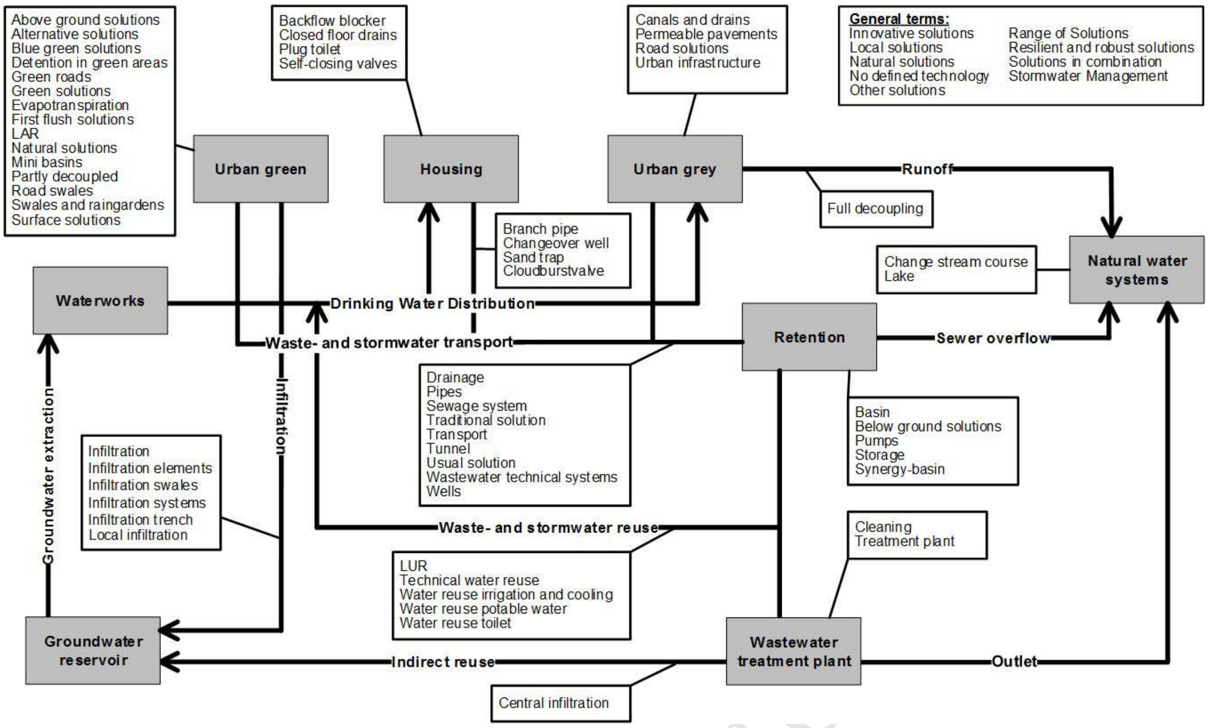
Case 3			
Actor type	**Event magnitude**	**Spatial scale**	**Goal**
Engineering consultant	service level	water catchment	reduce cost, prevent flooding damages, secure continuity, integrated with infrastructure
Engineering consultant	service level, level of security	water catchment	best society cost-benefit, added value, actor participation
Engineering consultant	design rain T=5, cloudburst	neighborhood	prevent flooding damages, integrated with infrastructure, reduce cost, land use planning, citizen participation, better water quality
Municipality	T=5/10, T=100	neighborhood	reduce volume in sewage, increase visibility, citizen participation, prevent flooding damages, prevent basement flooding, integrated with infrastructure
Municipality	T=5/10, level of security	water catchment, municipality	reduce cost, reduce overflows, appropriate groundwater levels, develop standard solutions, pleasing aesthetic, better water quality
Utility	T=5/10, cloudburst	utility, neighborhood	range of solutions, develop standards, reduce cost, reduce maintenance cost, prevent flooding damages, prevent overflows, citizen participation, appropriate expression
Utility	T=5/10, cloudburst	water catchment, sewage system	best society cost-benefit, prevent flooding damages, added value


Litterature review
Theoretical litterature study
Desription:
- Choice of theoretical background
Output:
- Interview guide informed by theory
Screening
Screening actor network
Description:
-Screening based on three informants
Output:
- Choice of main case
- Choice of context interviewees
Data Collection [R1]
Semi-structured interviews
Description:
- Main case, 8 context interviews performed
Analysis [R1]
8 context interviews
Descrioption:
- Transcribing 8 context interviews
- Coding of 8 context interviews
Output:
- Analytical framework
- Choice of embedded cases
Data Collection [R2]
Semi-structured interviews
Description:
-3 embedded cases, 24 (10/7/7) interviews performed
Analysis [R2]
24 case interviews
Description:
- Transcribing 24 case interviews
- Coding 24 case interviews
Output:
- Case narratives
- Outline of preliminary results
Analysis
32 interviews and litterature
Description:
- Analysis of 32 interviews and literature
Output:
Characterization of Climate Change Adaptation


Event magnitude
Extreme domain (64/116)
cloudburst; high water pressure; intensive rain events; level of security; service level for water on terrain; too much water; above normal water volumes; larger than design; range of events; chaos; extreme rain; large events; more rain; peak loads; full range; individual cloudburst; monster rain; torrential rain; heavy rain; 10 cm water on terrain; T=0.5/10/50/100
Design domain (47/116)
design rain; dimensioning rain; normal rain; service goals; service level; normal water volumes; ordinary rain; 50 mm rain; not T=100; not cloudburst T= 2/3.5/4/5/6.5/10/20
Everyday domain (5/116)
Everyday rain; T=1
Return period



Large, inter-/national (19/215):
international; national; overall solution; region; society
Medium, urban (120/215):
city; flood areas; hydraulic system; municipality; risk area; sewage system; system; utility; water catchment
Small, local (76/215):
cadaster; high rise association; homeowner's association; neighborhood; residential area; road; roads and roofs



Above ground solutions
Alternative solutions
Blue green solutions
Detention in green areas
Green roads
Green solutions
Evapotranspiration
First flush solutions
LAR
Natural solutions
Mini basins
Partly decoupled
Road swales
Swales and raingardens
Surface solutions
Backflow blocker
Closed floor drains
Plug toilet
Self-closing valves
Canals and drains
Permeable pavements
Road solutions
Urban infrastructure
General terms:
Innovative solutions
Local solutions
Natural solutions
No defined technology
Other solutions
Range of Solutions
Resilient and robust solutions
Solutions in combination
Stormwater Management
Urban green
Housing
Urban grey
Runoff
Full decoupling
Branch pipe
Changeover well
Sand trap
Cloudburstvalve
Change stream course
Lake
Natural water systems
Waterworks
Drinking Water Distribution
Retention
Sewer overflow
Waste- and stormwater transport
Drainage
Pipes
Sewage system
Traditional solution
Transport
Tunnel
Usual solution
Wastewater technical systems
Wells
Basin
Below ground solutions
Pumps
Storage
Synergy-basin
Groundwater extraction
Infiltration
Infiltration
Infiltration elements
Infiltration swales
Infiltration systems
Infiltration trench
Local infiltration
Waste- and stormwater reuse
Cleaning
Treatment plant
LUR
Technical water reuse
Water reuse irrigation and cooling
Water reuse potable water
Water reuse toilet
Groundwater reservoir
Indirect reuse
Wastewater treatment plant
Outlet
Central infiltration

- Definitions of climate change adaptation existing in practice are ambiguous
- Differences in actors' definitions leads to both conflict and potential innovation
- Ambiguous definitions negatively affects cities' capacity for change
- A clear and inclusive definition of climate change adaptation is necessary
- Important attributes include event magnitude, spatial scale, and goals